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# THE METALLURGICAL AND BALLISTIC CHARACTERIZATION OF QUARTER-SCALE TUNGSTEN ALLOY PENETRATORS


ROBERT J. DOWDING and KENNETH J. TAUER
MATERIALS PRODUCIBILITY BRANCH

PATRICK WOOLSEY and FRANK S. HODI
MATERIALS DYNAMICS BRANCH


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ABSTRACT

The microstructure, mechanical and physical properties, and ballistic performance of two lots of newly manufactured tungsten heavy alloy penetrators were evaluated. The microstructure and the measured properties met the purchase requirements and closely matched the properties of previously purchased material of similar composition. Ballistic testing revealed no noticeable effect on the depth of penetration of a semi-infinite, monolithic block of rolled homogeneous armor (RHA). In fact, all of the tungsten alloy materials that were tested performed in a linear manner over the velocity range tested with only a slight advantage observed for the Kennametal W-2 alloy due to its greater density. It was concluded that the material purchased would adequately serve the ballistic testing and armor development programs, and the mechanical properties were not significant in the depth of the penetration test. (JES)

## INTRODUCTION

The development of armor systems at the U.S. Army Materials Technology Laboratory (MTL) relies heavily upon scaled ballistic testing to determine their effectiveness. In order to provide a stable baseline to evaluate the armor packages, it is a necessary requirement that the ballistic projectile supply must be as uniform as possible. To achieve that stability, projectiles are purchased in large quantities or purchased in quantities sufficient to complete a program.

For the development of some armor packages, the projectile that best simulates the projected threat to the fielded armor system is a quarter-scale, kinetic energy, long-rod penetrator. The test projectile is made from a tungsten heavy alloy so chosen for its high density and good mechanical properties. These projectiles are generally purchased by competitive bid in lots of 500 from one of several manufacturers of the heavy alloy. However, a problem may arise when the supply of penetrators starts to run short and a new lot must be acquired. The problem is multi-faceted; due to reorganization and personnel turnover the records of the properties of the previous lot are often misplaced and, for the most part, unknown. All of these factors make it extremely difficult to draw-up a list of specifications that will satisfy the requirements of the ballistic test. In addition, the competitive bid system provides no guarantee that the supplier of the first lot will be the supplier of the second lot; this, in itself, will lead to variations in the penetrator supply. It is also noted that in the lifetime of a lot of penetrators there are likely to be improvements in the tungsten heavy alloy through more closely-controlled chemistry and processing conditions.

The purpose of this report is to document the properties of two lots of tungsten heavy alloy penetrators that have been recently received so that future purchases can be made more easily, and it will serve as a baseline by which improvements in the manufacturing of tungsten heavy alloys can be measured. This report will also serve as a resource guide to the users of the penetrators.

## THE PENETRATOR

The quarter-scale tungsten heavy alloy (WHA) has a simple design, as shown in Figure 1. It is a right-circular cylinder with a hemispherical nose with a length to diameter ratio of 10:1 and a mass of 65 grams. The geometry of the hemispherical nose is such that its radius is equal to the radius of the cylinder. With the alloy and, hence, density specified, these are the only specifications on geometry because the length and diameter will then be fixed. The penetrator diameter will be in the range of 0.300 inch to 0.310 inch depending upon the alloy, and the total length will be ten times the diameter.

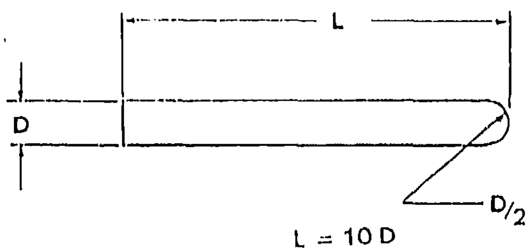


Figure 1. Quarter-scale penetrator, L/D = 10, mass 65 g.

## PROCUREMENT

Two lots of 500 penetrators each were ordered and received. The first lot was to be a 91% tungsten alloy with the balance being iron, nickel, and cobalt (the cobalt was optional). The second lot was to be 93% tungsten with the balance similar to the 91W alloy. The procurement specifications are given in Table 1.

Table 1. PROCUREMENT SPECIFICATIONS

| Property | 91W | 93W |
|---|---|---|
| Tensile Strength | 170 ksi | 180 ksi |
| Elongation | 15% | 6% |
| Density | 17.3 g/cc | 17.65 g/cc |
| Charpy Impact | 70 ft-lb | —— |
| Surface Finish | 63 RMS max. | 63 RMS max. |

NOTE: All values except surface finish are minimum requirements.

## CHEMICAL ANALYSIS

The contract for the supply of the penetrators was awarded to Teledyne Firth Sterling (TFS) of LaVergne, Tennessee. Two lots of quarter-scale penetrators were received in October, 1989 under Contract Number DAAL04-89-M-0637. The first lot was identified as Lot Number 1078 and was Teledyne Grade X21C, approximately 93% tungsten with the balance being nickel, iron, and cobalt. The second lot was identified as Lot Number 1079 and was Teledyne Grade X27C, approximately 90% tungsten with the balance also being nickel, iron, and cobalt. The manufacturer supplied a certificate of chemical analysis that identified the major components of each alloy, and this analysis is shown in Table 2.

Table 2. CHEMICAL ANALYSIS
(Weight Percent)

| Element | Lot No. 1079 X27C | Lot No. 1078 X21C |
|---|---|---|
| Tungsten | 90.73 | 92.90 |
| Nickel | 4.55 | 3.51 |
| Iron | 1.97 | 1.47 |
| Cobalt | 2.75 | 2.12 |

## PHYSICAL PROPERTIES

Various physical properties were measured at MTL. Most importantly, the density of each type of penetrator was determined by Archimedes' method. The density of the X21C was found to be 17.57 g/cc, and the density of the X27C was determined to be 17.45 g/cc; each is the average of three readings. The dimensions and the mass of a representative sampling of penetrators were measured, and a summary is shown in Table 3.

Table 3. DIMENSIONS AND MASS

| Grade | Length (in.) | Diameter (in.) | Mass (g) |
|---|---|---|---|
| X21C | 3.070<br>$\sigma = 0.002$ | 0.307<br>$\sigma = 0.0003$ | 64.94<br>$\sigma = 0.12$ |
| X27C | 3.100<br>$\sigma = 0.0008$ | 0.3099<br>$\sigma = 0.0002$ | 65.40<br>$\sigma = 0.053$ |

## MECHANICAL PROPERTIES

The usual mechanical property data was obtained at MTL, and some of the data was given in the certification supplied by TFS. This data is compared if it was obtained by both laboratories. The mechanical property data, collected previously for the Teledyne X27 from 1986 and similar data for Kennametal W-2 alloy, are also shown. The mechanical properties are shown in Table 4.

Table 4. MECHANICAL PROPERTIES

| Grade | 0.2 % Yield (ksi) | UTS (ksi) | R.A. (%) | Elongation (%) | Impact (ft-lb) |
|---|---|---|---|---|---|
| X21C (MTL) | 187.9 | 193.2 | 10.4 | 10.8 | — |
| X21C (TFS) | — | 187.3 | — | 10.1 | 106 |
| X27C (MTL) | 169.4 | 171.0 | 16.8 | 11.9 | — |
| X27C (TFS) | — | 170.3 | — | 14.4 | 180 |
| X27 (1986) | 171.0 | 174.0 | 20.4 | — | — |
| W-2 (1983) | 149.2 | 150.3 | 1.8 | 3.1 | — |

**Note:** The reader should be aware that the alloy X27C is a refinement of the earlier X27 alloy by TFS. The nominal tungsten content is the same for both alloys, but the matrix of the X27C alloy contains cobalt, whereas the X27 contained no cobalt.

The macrohardness of the penetrators was measured; this is an important, simple test because it is related to the yield strength and is also a measure of the amount of cold working. The Rockwell hardness was measured on the direct "C" (HRC) scale. The hardness of the X21C is HRC 39.4 ± 0.8, and the hardness of the X27C is HRC 38.6 ± 0.5. By way of comparison, the hardness of the X27 was HRC 37.1 and the hardness of the W-2 is HRC 37.6.

## MICROSTRUCTURE

The microstructure of each lot was examined in the transverse and longitudinal cross sections. Figures 2 and 3 illustrate the grain size and shape of the X21C and X27C, respectively, in the transverse cross section. The tungsten grain size, measured in the longitudinal cross section, of the X21C is approximately 25 $\mu$m and the grain size of the X27C is 16.4 $\mu$m. The elongated grain shape seen in these views are a result of cold working. The aspect ratio of the tungsten grains in the X21C alloy is 1.6 and the ratio of the X27C grains is 1.5.

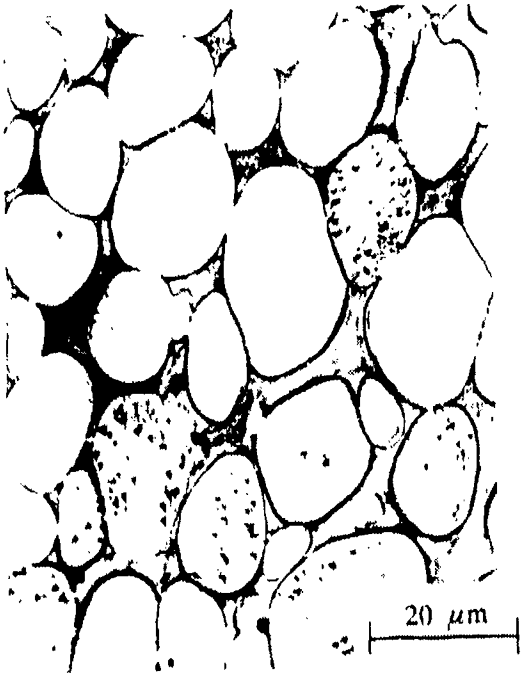


Figure 2. Microstructure of X21C. The round particles are tungsten and the material between them is the matrix. The tungsten grain size is 25.1 μm and the grain aspect ratio is 1.6:1. This sample was etched with Murakami's reagent.

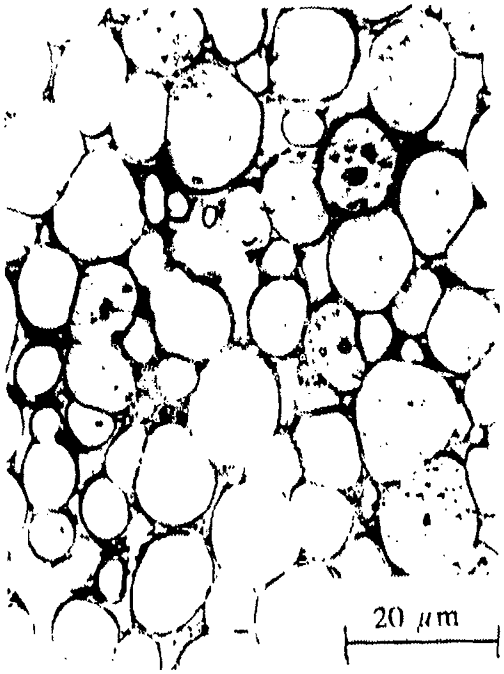


Figure 3. Microstructure of X27C. The round particles are tungsten and the material between them is the matrix. The tungsten grain size is 16.4 μm and the grain aspect ratio is 1.5:1. This sample was etched with Murakami's reagent.

## BALLISTIC EVALUATION

The major concern related to penetrator materials is consistency of ballistic performance from lot to lot. Changes in the chemistry and microstructure exhibited by the X27C in comparison to the previous X27 rod, which has been a standard test penetrator for a variety of work, necessitated the determination of what variations in ballistic performance might occur. Ballistic tests were conducted at MTL using three types of rods: Teledyne X27C, X21C, and a Kennametal W-2 alloy from a lot purchased in 1983 with a density of 18.6 g/cc, launched from a 20 mm smooth-bore powder gun with appropriate sabot packages. The target employed was a semi-infinite block of monolithic rolled homogeneous armor (RHA) steel (MIL-A-12560, Class 3) with an average hardness of 27 HRC. The penetrator struck the target at 0° obliquity. Depths of penetration were obtained by direct measurement from saw-cut sections of the RHA block. The resultant data obtained are expressed in terms of the depth of penetration into the steel block as a function of velocity, as shown in Figure 4. Data used to produce this plot were from shots with less than 3° total yaw, as previous studies at MTL and Ballistic Research Laboratory (BRL) indicated this as an appropriate cutoff point.[1,2,3] A graphical indication of this is shown in Figure 5 where penetration is plotted against yaw for shots having a velocity of 4900 ± 25 ft/sec. The variation in depth of penetration due to fluctuation in velocity is only ± 0.025 inch, so the reduction in performance due to yaw is obvious.

1. WOOLSEY, P., KOKIDKO, D., and MARIANO, S. *Alternative Test Methodology for Ballistic Performance Ranking of Armor Ceramics.* U.S. Army Materials Technology Laboratory, MTL TR 89-43, April, 1989.
2. ZUKAS, J. A. et al. *Impact Dynamics.* J. Wiley and Sons, New York, 1982.
3. WOOLSEY, P., KOKIDKO, D., and MARIANO, S. *Progress Report on Ballistic Test Methodology for Armor Ceramics.* U.S. Army Materials Technology Laboratory, Presented at TACOM Combat Vehicle Survivability Symposium, March, 1990.

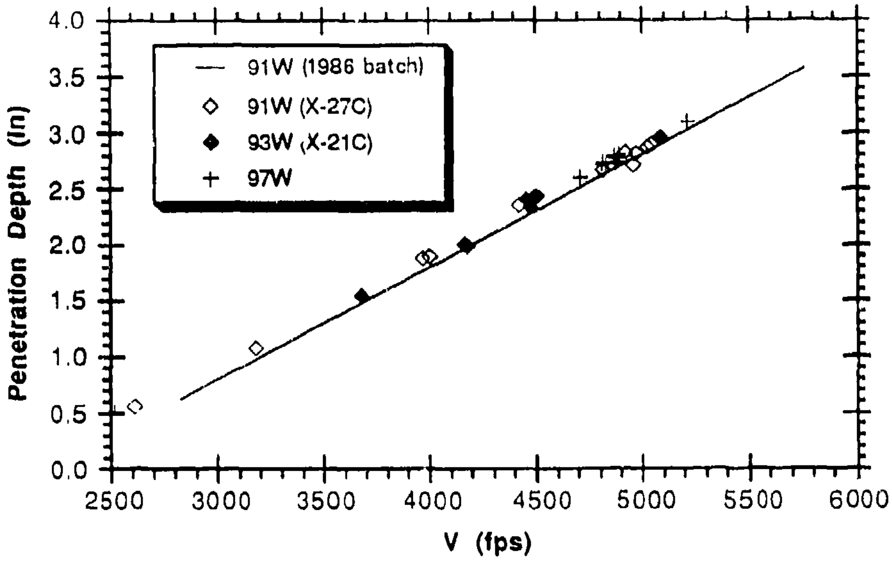


Figure 4. Depth of projectile penetration versus projectile velocity. The target was a monolithic block of semi-infinite rolled homogeneous armor struck at 0° obliquity.

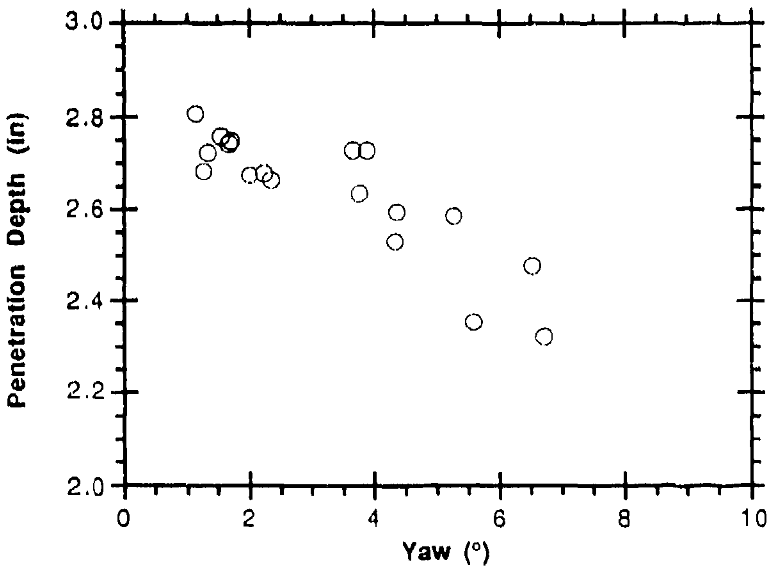


Figure 5. Effect of yaw on penetration depth of tungsten heavy metal projectiles at constant projectile velocity (4900 ft/sec).

The line plotted in Figure 4 is the equation of fit determined for a large number of shots taken with the original MTL purchased X27 rod. Comparative data for the Teledyne X-nnC alloys, as well as the Kennametal W-2 rod, are shown as individual points. The behavior of all penetrators over this velocity range is linear. Of particular interest is the lack of differentiation between the various materials despite significant strength variations. Only the 97W rods exhibit an average behavior which is greater than the inherent scatter in the test results. These results suggest that only density is a noticeable driver of performance in this type of target which means that the mechanical property requirements of the rod for use under similar test conditions need not be extremely stringent. A word of warning should be given, however, with regard to possible extrapolation of these results to other applications. Results in targets which impose significant bending moments; i.e., triple plate tests, on the rods or under conditions where launch loads are less symmetrical, may show greater performance variations between WHA materials.

## CONCLUSIONS

The results of the mechanical and microstructural examinations indicate that the material received meets the purchase specification. It was found that the mechanical properties of the test material received in 1989 were nearly identical to the material received in 1986. More importantly, it was discovered that the mechanical properties have little influence on the depth of penetration ballistic test. It was also observed that density is apparently the only driver of performance in this type of test as indicated by the performance of the W-2 alloy which has much poorer mechanical properties but greater density.

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